



D4.3 A dynamic LCA/LCCA open source toolkit

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Table of Content

.....	1
Index of Figures	8
Index of Tables.....	8
Table of Abbreviations and Acronyms	9
Executive summary	10
1 Introduction to the deliverable	11
1.1 Structure of the deliverable	11
1.2 Relevant documents	11
2 Introduction to dynamic (real-time) LCA/LCC	13
2.1 The need for automating LCA and LCC	13
2.2 Introduction to the ECOFACT approach to dynamic LCA and LCC.....	13
3 The ECOFACT approach to performing dynamic LCA/LCC	15
3.1 The technical solution.....	15
3.1.1 Edge layer: Sensors/meters and the Local Data Acquisition Systems	15
3.1.2 The Data Broker layer	17
3.1.3 The Apps and Services layer	17
3.2 Steps for carrying out a dynamic LCA/LCC study for a manufacturing company	17
3.2.1 Step 1: Define goal and scope of the LCA and LCC models	17
3.2.2 Step 2: Identify data requirements	18
3.2.3 Step 3: Map the required data to data sources	18
3.2.4 Step 4: Create parameterized LCA and LCC model of factory processes	18
3.2.5 Step 5: Calculate baseline results	18
3.2.6 Step 6: Define and evaluate scenarios, perform sensitivity analysis and	18
refine models.....	18
3.2.7 Step 7: Set up live link to feed data to the LCA/LCC models	19
3.2.8 Step 8: Configure data management and storing.....	20
3.2.9 Step 9: Configure dashboards	20
3.2.10 Step 10: Configure decision support functionality	20
3.2.11 Step 11: Continuously monitor and improve	21
4 Demonstration of the approach using a hypothetical factory as an example.....	22
4.1 Description of the hypothetical factory.....	23
4.2 Demonstration of the steps in the ECOFACT approach to dynamic LCA and LCC	24
4.2.1 Step 1: Define the goal and scope of LCA and LCC models	24



4.2.2	Step 2: Identify data requirements	25
4.2.3	Step 3: Map the required data to data sources	26
4.2.4	Step 4: Create parametrized LCA/LCC models of the factory processes	27
4.2.5	Step 5: Calculate baseline results	27
4.2.6	Step 7: Set up live link to feed data to the LCA/LCC models	27
4.2.7	Step 8: Configure data management and storing.....	36
4.2.8	Step 9: Configure dashboards	36
4.2.9	Step 11: Continuously monitor and improve	36
5	Discussion.....	40
5.1	Dynamic LCA vs traditional LCA	40
5.2	On demand calculation requests and additional logic	40
5.3	Life cycle costing	40
5.4	Future potential of real-time LCA: predictive analytics.....	40
6	Conclusions.....	42
	References.....	43



Index of Figures

Figure 1: Schematic overview of the ECOFACT solution. The LCA/LCC module is highlighted red colour.	15
Figure 2: Steps on sensitivity analysis of critical parameters	19
Figure 3: Information flow from the factory to the ECOFACT platform – to the LCA module (green box) – and back to the ECOFACT platform.	23
Figure 4: Hypothetical factory parametrized flowchart.....	24
Figure 5: Carbon footprint per time interval	37

Index of Tables

Table 1: Relevant documents for this deliverable.....	12
Table 2: LCA model parameters description	24
Table 3: Dynamic data points and update frequency.....	25
Table 4: Data sources for dynamic data points.....	26
Table 5: Model parameters and their updated values per time interval	34



Table of Abbreviations and Acronyms

AB	Athenian Brewery
AHP	Analytical Hierarchy Process
API	Application Programming Interface
ARC	Arçelik
BMS	Building Management System
DSS	Decision Support System
EF	Environmental Footprint
GUL	Gullon
ICT	Information and Communications Technology
IoT	Internet-of-Things
IPCC	Intergovernmental Panel on Climate Change
JSON	JavaScript Object Notation
KPI	Key Performance Indicator
LCA	Life Cycle Assessment
LCC	Life Cycle Costing
LCCA	Life Cycle Costing Analysis
LCIA	Life Cycle Impact Assessment
REST	Representational State Transfer
SaaS	Software as a Service
SCADA	Supervisory Control and Data Acquisition
TOF	Tofaş
UI	User Interface



Executive summary

The deliverable provides an open source toolkit on how to perform a dynamic (real-time) Life Cycle Assessment (LCA) and Life Cycle Costing (LCC) in a factory environment. It shows the role of the Application Programming Interface (API) for the online LCA/LCC module in enabling environmental footprint calculations in real-time and at scale. Note that the abbreviation LCCA used in the document title stands for Life Cycle Costing Analysis. This is synonymous to LCC, but since LCC is a more commonly used term, we consistently use LCC throughout this document.

Specifically, this deliverable describes how to perform dynamic LCA and LCC the way that it is done in the ECOFACT project. This requires (1) a technical solution, such as the ECOFACT platform, and (2) a number of steps to set up the specific LCA/LCC module and configure the information flows for the specific factory site.

The ECOFACT technical solution is briefly discussed in this deliverable. It consists of three main layers: the edge layer, the data broker layer and the apps and services layer.

The steps for setting up the LCA/LCC module and configuring the information flows for a factory are discussed and demonstrated in detail. Specifically, the steps identified are the following:

- Step 1: Define the goal and scope of LCA and LCC models
- Step 2: Identify data requirements
- Step 3: Map the required data to data sources
- Step 4: Create parameterized LCA and LCC model of factory processes
- Step 5: Calculate baseline results
- Step 6: Define and evaluate scenarios, perform sensitivity analysis and refine models
- Step 7: Set up live link to feed data to the LCA/LCC models
- Step 8: Configure data management and storing
- Step 9: Configure dashboards
- Step 10: Configuring decision support functionality
- Step 11: Continuously monitor and improve

Finally, the main steps on performing a dynamic, real-time LCA/LCC, using the SimaPro API solution, is demonstrated.



1 Introduction to the deliverable

1.1 Structure of the deliverable

This deliverable is structured as follows. Chapter 2 introduces the idea of dynamic (real-time) LCA and LCC. It discusses the (1) need for scaling up LCA/LCC calculations, (2) the differences between dynamic and static LCA, (3) the role of an API to call an LCA/LCC software module to enable dynamic calculations, and (4) how new insights derived from the dynamic LCA/LCC models can be translated into targeted actions to improve a factory's environmental performance. Chapter 3 describes what is needed to perform a dynamic (real-time) LCA and LCC in a factory environment. First, the ECOFACT technical solution is briefly introduced. Secondly, the steps for carrying out a dynamic LCA/LCC study are described. Chapter 4 demonstrates the main steps of performing a dynamic, real-time automated LCA/LCC using a hypothetical factory as an example. In this example, the SimaPro software and its API solution is used, but the general idea would be similar also for other software solutions. Chapter 5 provides a discussion on performing dynamic LCA/LCC as well as a discussion about its future potential. Finally, chapter 6 states the overall conclusions based on the work presented in this deliverable.

It should be noted that the term “*dynamic LCA*” has been used in previous literature in different contexts, meaning different things. For example, “*dynamic LCA*” can mean that the characterisation factors of an impact assessment method are adjusted for any given time horizon. In this report, we therefore use the term “*real-time*” to emphasize what we mean by “*dynamic LCA*”, i.e. that the calculation of the impacts takes place in short time intervals (compared to traditional LCA timescales), using updated life cycle inventory data collected from the factory sites. The term “*real-time*” LCA/LCC is thus used to enhance the understanding of “*dynamic LCA*” and it should not be confused with the “*real-time*” concept that is used in the automatization application or communication systems sectors.

The update frequency of the data coming from the factories can vary. For example, electricity data might be measured every second, while waste data might only be updated every month. We want to clarify that because of the nature of LCA to evaluate the impact per functional unit, there is always a minimal time interval for which results can be calculated: the time interval must at least be long enough to generate some function as defined by the functional unit. In the case of ECOFACT, this means that each time interval for which a calculation is made must be associated with some volume of production of the product produced in the factory. The frequency at which calculations take place is thus, in most cases, longer than the shortest frequency of incoming data.

1.2 Relevant documents

Table 1 shows the documents that are relevant or related to D4.3.



Table 1: Relevant documents for this deliverable

Deliverable number	Deliverable title
D1.1	Mapping of manufacturing sectors for ECOFACT application
D1.2	Holistic baseline characterization and boundary conditions for ECOFACT industrial sites
D1.3	ECOFACT methodology and holistic management guidelines
D1.4	KPI-based ECOFACT reference framework
D2.1	Design of an architecture for decentralized monitoring networks
D4.1	Mapping of data sources for dynamic LCA/LCCA
D4.2	ECOFACT Supply Chain Collaboration service
D4.4	Sensitivity analysis for optimization of the dynamic LCA/LCCA process
D4.5	AHP decision making algorithms
D4.6	Parameterised LCA/LCCA models for ECOFACT demonstration cases
D5.1	ECOFACT platform architecture and common IT framework
D5.3	Report on ECOFACT APIs for enabled service communication
D5.4	ECOFACT holistic Decision-Support System. Algorithms and tests
D5.7	Follow up of the ECOFACT development and fine tuning. Interim report
D5.8	Follow up of the ECOFACT development and fine tuning. Final report



2 Introduction to dynamic (real-time) LCA/LCC

2.1 The need for automating LCA and LCC

It is widely acknowledged that organisations around the world are aiming to improve the eco-profile of their products and the sustainability performance of their operations [1]. There is a growing trend of monitoring environmental impacts of a product or service throughout the life-cycle. This has created a high demand for life cycle information and for broadly applicable methods and tools to calculate the ecological footprint.

Life Cycle Assessment (LCA) is a standardized and widely applicable method to calculate the total environmental impacts associated with a product or service over its life cycle. Furthermore, LCA can be combined with Life Cycle Costing (LCC), which is a method to evaluate costs associated with a product throughout its life-cycle [2]. Insights from LCA/LCC can help companies identify opportunities for processes optimisation, considering both environmental and economic objectives [3].

As the demand for versatile and reliable LCA results is rapidly increasing, automated and large-scale solutions are needed. Current LCA practice relies on stand-alone studies and static documentation, which is based on average values from a limited temporary scope, usually one year. The time and effort required to update results for different time periods can be significant. As input data quickly gets outdated, it is of large interest to develop technical solutions that can automate data and collection and provide updated LCA/LCC results over time. Such a dynamic approach to LCA/LCC can help improve the efficiency of the assessments and streamline data management for large-scale applications.

2.2 Introduction to the ECOFACT approach to dynamic LCA and LCC

In the ECOFACT project, dynamic LCA and LCC is demonstrated in four factories. By implementing dynamic LCA/LCC in practice, an important goal is to generate learnings that can support a wider application dynamic LCA and LCC. In comparison to static modelling, dynamic LCA and LCC models can improve the accuracy of the results. While static LCA and LCC can only deliver a snapshot of environmental impacts and costs for a fixed period, a dynamic approach enables insights into temporal variations. This can enable companies to observe patterns in how the results vary depending on, for example, seasonal changes and operational parameters.

Dynamic LCA and LCC assessments require readily available high-quality data. To facilitate this, the ECOFACT approach is based on internet-of-things (IoT) technologies that collect relevant data from the factory site and connect to the ECOFACT platform which can direct the data through an API request to the LCA/LCC software module containing the LCA/LCC models. This way, it becomes possible to use real-time data from a local data acquisition system installed in a factory as input when calculating life cycle environmental impacts and costs.



The goal is that insights achieved from the dynamic LCA and LCC can be translated into targeted actions to improve a factory's performance. For instance, shifting production to specific days of the week or even specific hours during the day when LCA impacts are low can improve the eco-profile of the factory.

Again as discussed in the section 1.1, the term "*real-time*" strictly refers to the LCA/LCC and is used to enhance the understanding of dynamic LCA and it should not be confused with the "*real-time*" concept that is used in the automatization application or communication systems sectors.



3 The ECOFACT approach to performing dynamic LCA/LCC

To perform dynamic LCA and LCC the way that it is done in the ECOFACT project requires (1) a technical solution, such as the ECOFACT platform, and (2) a number of steps to set up the specific LCA/LCC module and configure the information flows for the specific factory site.

The ECOFACT platform is applied in four factories (demo sites) that are part of the project consortium (Athenian Brewery, Arçelik, Gullón and Tofaş).

3.1 The technical solution

The ECOFACT solution consists of three main layers: the edge layer, the data broker layer and the apps and services layer, as depicted in Figure 1. The edge layer is the layer installed at the manufacturing site and is not part of the ECOFACT platform itself. Finally, the ECOFACT platform includes a Configuration and Monitoring Framework, used to configure and monitor the platform components in real time through the ECOFACT Platform Manager.

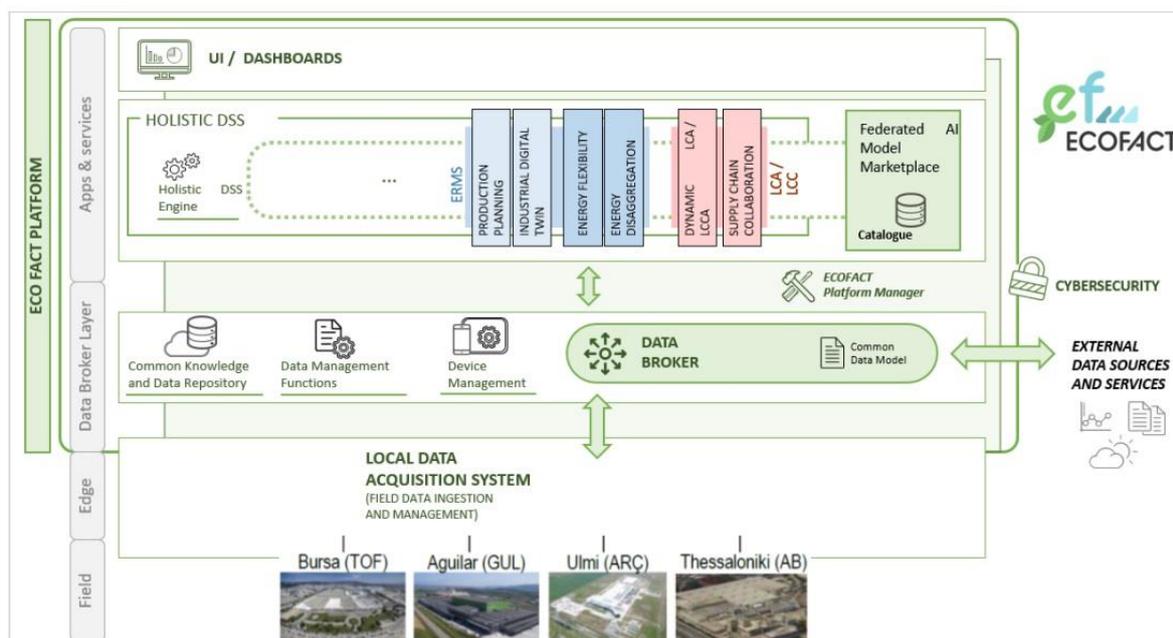


Figure 1: Schematic overview of the ECOFACT solution. The LCA/LCC module is highlighted red colour.

In this section, the ECOFACT technical solution is presented briefly to allow the reader to understand how the dynamic LCA/LCC calculations take place. More details about the platform architecture are available in Deliverable 5.1.

3.1.1 Edge layer: Sensors/meters and the Local Data Acquisition Systems

To feed the LCA and LCC models, data about energy, water, material flows and costs from the manufacturing site is needed. Some of the data will come from sensors and measurement devices installed at the demo factory site (see subsection 3.1.1.1). When applicable, dynamic data can also be collected from suppliers (see subsection 3.1.1.2).

Finally, some data points might have to be inputted directly to the ECOFACT platform (see subsection 3.1.1.3).

3.1.1.1 Data from sensors and measurement devices at the demo factory site

Data from sensors and measurement devices installed at the demo factory site is collected and stored in a Local Data Acquisition System for the field data ingestion and management. The ECOFACT project uses existing platforms offered by the ECOFACT partners Schneider (EcoStruxure¹), Wings (ARTEMIS²) and Smarkia (Smarkia³).

A set of services will be added to the Local Data Acquisition System within the Edge Layer (Figure 1), which establishes a flexible IoT monitoring network capable of collecting and homogenizing the acquired data between the high variety of different communication protocols and hardware interfaces at different levels using a common data model. These services are provided by the following three main components, included in the uniform part of the edge layer:

- The data broker for demo site (factory) specific platforms which is a component that takes data from the platform and harmonize them. This component will be composed by a data broker that provide to the integrated platforms means to send the data using the heterogenous protocols they support.
- The normalized database is the component that stores the data in a database, where all the data are already stored using the common data model. The database is also used to store the data locally, in case the connection with the ECOFACT platform is temporally not available.
- The API to ECOFACT platform module, which sends the data to the cloud based ECOFACT platform and is the interface for data exchange with the Energy and Resource Management System and the Dynamic LCA/LCC.

More details about the edge layer are available in Deliverable 2.1.

3.1.1.2 Data from other supply chain actors

If relevant, data from suppliers can also be integrated to the ECOFACT platform. This means that the LCA/LCC results will vary dynamically depending on the environmental performance of the production of the supplied material or component. This can be interesting if this material or component has a significant effect on the total life cycle impact or cost.

To make relevant data from the supplied items available, ECOFACT includes supply chain collaboration service. This service establishes a bidirectional flow of relevant information between suppliers and producers, ensuring that the data format complies with the rest of the platform. More information about the supply chain collaboration service is available in Deliverable 4.2.

¹ <https://www.se.com/ww/en/work/campaign/innovation/platform.jsp>

² <https://www.wings-ict-solutions.eu/artemis/>

³ <https://www.smarkia.com/en>



3.1.1.3 Data that cannot be collected automatically

Some data might not be possible to collect automatically. This data will instead be inputted directly into the ECOFACT platform by a platform user. This could, for example, be data about specific costs or about material flows in the factory for which there is not (yet) an automatic measurement system.

3.1.2 The Data Broker layer

The Data Broker Layer provides tools to aggregate and push data to consumers, building a communication system between the interacting ICT components. It provides means to publish and subscribe to streams/topics of records to process them real-time and to store them. It also provides functionalities of device management and enable the interaction with external services. Furthermore, the Data Broker Layer provides the common data model, which needs to be used by all the components to make them interoperable with each other.

The main component of the Data Broker Layer is the data broker, which acts as a central hub in the ECOFACT solution, directing data between different modules. The data broker also stores data in a common knowledge and data repository, which other platform modules can access via an API.

More information about the data broker will be provided in Deliverable 5.3.

3.1.3 The Apps and Services layer

The Apps & Services Layer includes tools that provide a set of advanced data analyses and service recommendations. It will host the tools for LCA and LCC calculation and the Energy and Resource Management System. Furthermore, it will provide the Holistic Decision Support Tool that supports decision-making processes for platform users. It will integrate a federated marketplace to allow for easy deployment and distribution of ECOFACT modules. Finally, it will provide the interfaces needed by the stakeholders to use the services provided by the platform, supporting a multi-tenant approach.

This layer includes the Holistic Decision Support Tool. This tool can trigger requests of calculations and receives results (both via the data broker) from the cloud-based LCA/LCC module where the parametrised LCA/LCC models are implemented. Such requests can be also triggered through the ECOFACT UI/Dashboard or by other components, also in this case, via the data broker.

More information about the Apps and Services layer will be available in the forthcoming Deliverables 5.4, 5.7 and 5.8.

3.2 Steps for carrying out a dynamic LCA/LCC study for a manufacturing company

This section describes the steps needed to set up the specific LCA/LCC module and configure the information flows for the specific factory site.

3.2.1 Step 1: Define goal and scope of the LCA and LCC models

This step includes describing the system boundaries and defining the environmental and cost KPIs to be calculated. This step is the same as for a conventional static LCA. In ECOFACT demonstration cases, the goal for the LCA and LCC models is to continuously



monitor environmental impact and costs of the factory as a whole and in relation to a unit of the manufactured product. This includes continuous identification of hotspots, i.e., processes with high contribution to the environmental impacts. Environmental KPIs include a selection of the impact categories from the EF 3.0 impact assessment method [4], as well as total energy consumption and total resource consumption. Cost KPIs include, for example, energy costs, maintenance costs and waste management costs.

3.2.2 Step 2: Identify data requirements

Based on the goal and scope, the next step is to list the data requirements for performing the desired analysis. This step is the same as for a conventional static LCA. Important data points include, for example, the product bill of materials, energy consumption of different process steps, water use, material inputs and waste amounts. Identifying the data requirements also includes specifying which data points will be dynamic, i.e., continuously updated, and which can be considered static.

3.2.3 Step 3: Map the required data to data sources

For the dynamic data points, it is necessary to make a detailed map of the data sources from which the data will be collected. The data sources can be sensors, meters, management systems, but also manual input from users. Apart from using data sources from the manufacturing company itself, the ECOFACT project also demonstrates the integration of dynamic data from a supplier. If this mapping step reveals that additional components for automated data collection are desirable, such installations should be detailed and planned.

3.2.4 Step 4: Create parameterized LCA and LCC model of factory processes

The next step is to build the model that will use the data identified in the previous steps. The models need to be parameterized, meaning that inputs are defined as parameters that are updated when new data becomes available. This results in a dynamic model that continuously calculates updated impact results. The first version of the model can use input values based on historical data from the factory. This step also includes to set up a customized impact assessment method in the LCA/LCC software, so that when calculation request is sent through the API, the results of all desired indicators are returned.

3.2.5 Step 5: Calculate baseline results

When a model is in place, a baseline result can be obtained based on historical data. The results are calculated based on specific selected KPIs including both environmental and cost indicators. The baseline results give initial insights into environmental and cost hotspots. At this stage, it might be decided to modify the model or the data requirements. For instance, if a certain process has a minor effect on the total results, data from that process might not have to be measured dynamically, thereby reducing unnecessary data transfer and processing.

3.2.6 Step 6: Define and evaluate scenarios, perform sensitivity analysis and refine models

Based on the preliminary results of the baseline scenarios obtained in the previous step, critical parameters are identified. Critical parameters are those parameters that have a large influence on the results. The critical parameters provide a starting point to



perform a sensitivity analysis on the results with the goal to provide insights on the type of actions that would be effective for the company to pursue, and potential suggestions to reduce the environmental footprint.

The critical parameters, based on their connection to the ECOFACT interventions to each demo site, can be distinguished in two categories: i) Primary Parameters (directly affected by the ECOFACT interventions), ii) Secondary Parameters (not affected by the ECOFACT interventions). For each demo case, different parameters will be identified, based on the baseline results.

The critical parameters are used to develop different scenarios as part of a sensitivity analysis regarding the results of each demo case. The overall approach on sensitivity analysis is presented in Figure 2.

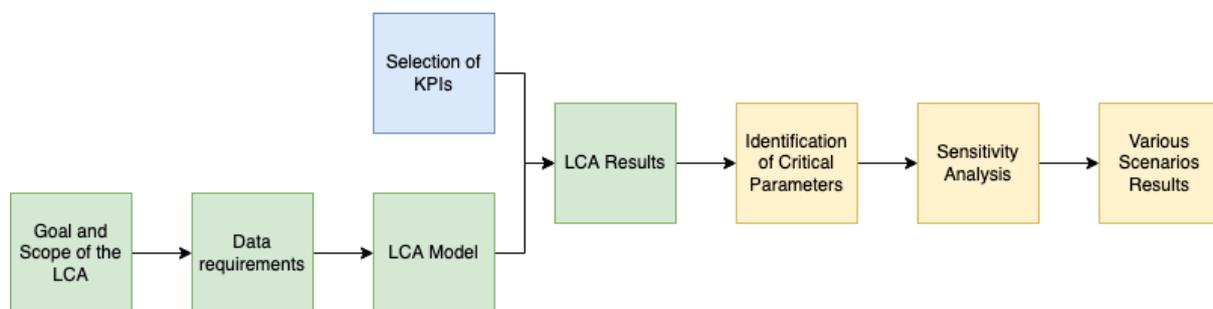


Figure 2: Steps on sensitivity analysis of critical parameters

Sensitivity analysis of the results is able to provide additional information regarding potential actions that would be effective for the company to decrease their overall environmental impacts. Depending on the user's needs, it is possible to create targeted scenarios to be evaluated. Furthermore, the sensitivity analysis can be used as feedback to modify the original LCA model, or the defined inventory/data requirements.

More information about the sensitivity analysis carried out for the ECOFACT demonstration factories will be provided in Deliverable 4.5.

3.2.7 Step 7: Set up live link to feed data to the LCA/LCC models

Steps 5 and 6 presented how results can be retrieved based on historical data and future scenarios. The next step is to set up the system to provide continuous monitoring of LCA and LCC results based on dynamic input data. For this to work, a "live link" that sends and receives data between the platform and the LCA/LCC module needs to be established. In the ECOFACT project, where the models are built in the online software SimaPro Flow [5], this link is realized through using a custom-built SimaPro API [6].

The platform will connect to the LCA/LCC software module to request LCA/LCC results based on updated data from common knowledge and data repository system. To enable this, a "wrapper" component will be developed to make the API calls required to request LCA/LCC results based on updated data, and to store these results in the common data repository.

LCA/LCC calculation requests will take place at a defined frequencies, or when requested by the user through the UI/Dashboard or by other platform modules.

Sending and receiving data between the different systems is done in a controlled, standardized and secure way. The SimaPro API is a REST API provided over an HTTPS protocol. Using the SimaPro API requires access to the SimaPro Platform using a username (email) and a password.

Updated LCA/LCC results can also be requested on demand, for instance when a user wants to assess the impact of an action that took place in the factory.

The following API requests are necessary to get updated LCA/LCC results:

1. Login/Authentication: POST request to receive an API access token.
2. Calculation: POST request to start an LCA/LCC calculation with updated values from the factory.
3. Calculation Status (Optional): GET request to retrieve the state of the calculation.
4. Calculation Results: POST request to retrieve the results of the LCA/LCC calculation from step 2.

Thus, the following are required to setup the live link using the SimaPro API:

- User credentials (email and password) that provide access to the online LCA/LCC software module to be used in the login/authentication request.
- The project id for the online parametrized LCA/LCC model to be used in the calculation request.
- The list of parameters of the parametrized LCA/LCC model as defined in the data mapping step to be used in the calculation request. The values of the parameters will be updated for each new calculation request with new data from the factory (per time interval or on demand).

A detailed demonstration of this step is provided in chapter 4.

3.2.8 Step 8: Configure data management and storing

As discussed earlier, the LCA and LCC models need to be parameterized, meaning that inputs are defined as parameters that are updated when new data becomes available. To be able to keep track of historic records, the list of parameters and their values per moment in time need to be stored. This can be done by storing the parameter set for each API calculation request. The parameter set will have a unique id. When one wants to retrieve historic results from a past moment, an impact calculation request can be sent to the online LCA/LCC module using the parameter set id from that past moment. In that way past results can be reproduced and reused.

3.2.9 Step 9: Configure dashboards

The results of the LCA/LCC will be visualized in dashboards. One can set up different dashboards for different users and customize them to the detail and time resolution that different users need based on their responsibility and influence. This makes the application flexible. Dashboards can include trends, seasonal variations or other variabilities.

3.2.10 Step 10: Configure decision support functionality

The results from the LCA and LCC can also be further processed to support decisions. In ECOFACT, a decision support module will be implemented which uses an analytical hierarchy process (AHP) algorithm for prioritizing possible actions. This is an efficient



multi-criteria decision-making method that facilitates the identification of the most appropriate good practice where there are multiple options. The algorithm takes user preferences into account by letting the user prioritize KPIs according to their relative importance.

More information about the AHP algorithm will be provided in Deliverable 4.4.

3.2.11 Step 11: Continuously monitor and improve

The ECOFACT platform will provide continuously updated environmental impact and cost results to the factories. The final step is thus to monitor these results over time and use these insights as guidance for continuous improvements with regards to energy, resource use and life cycle impact. Finally, the LCA/LCC module will be used not only for continuous monitoring on pre-specified time-intervals, but also for on demand calculations on specific KPIs of interest of the tool's users or other ECOFACT modules.



4 Demonstration of the approach using a hypothetical factory as an example

The main steps on performing a real-time automated LCA/LCC, discussed earlier in chapter 3.2, are demonstrated in this chapter. The focus of the demonstration is on LCA. Because the models of the four demo factories within ECOFACT are confidential, and for simplicity reasons, a hypothetical simplified factory is used as an example. This example factory is described in section 4.1.

In section 4.2, a step by step guide on how to set up a dynamic LCA/LCC using the SimaPro API is presented for this hypothetical factory.

The main steps that are demonstrated in this chapter are:

- Step 1: Define the goal and scope of LCA and LCC models
- Step 2: Identify data requirements
- Step 3: Map the required data to data sources (discussed qualitatively)
- Step 4: Create parameterized LCA and LCC model of factory processes
- Step 5: Calculate baseline results
- Step 7: Set up live link to feed data to the LCA/LCC models
- Step 8: Configure data management and storing (discussed qualitatively)
- Step 9: Configure dashboards
- Step 11: Continuously monitor and improve

The following steps are not demonstrated:

- Step 6: Define and evaluate scenarios, perform sensitivity analysis and refine models
- Step 10: Configure decision support functionality

In particular, because the model is based on a hypothetical factory it is assumed that all relevant parameters are considered. Thus, step 6 sensitivity analysis will not be demonstrated. Furthermore, step 6 will be dealt in detail in Deliverable 4.5. Step 10 has not yet taken place in the ECOFACT project, and is therefore not included in the demonstration. More information on step 10 will be provided in the forthcoming Deliverable 4.4.

All relevant technical components required for performing dynamic LCA/LCC, that were described in chapter 3, are assumed to be in place for this demonstration example.

Figure 3 shows the information flow from the factory to the LCA/LCC module (which is the SimaPro SaaS online platform in this project) and to the ECOFACT platform. The focus of the demonstration is on the actions related to LCA SaaS (highlighted with a green colour in Figure 3).



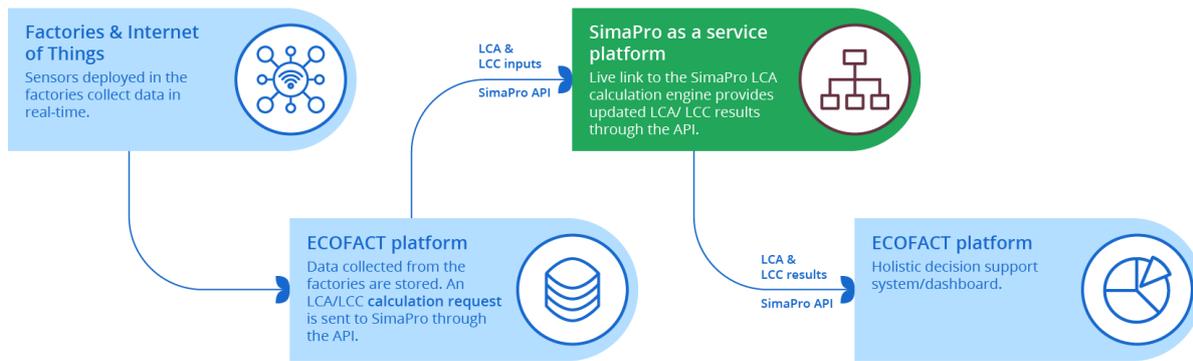


Figure 3: Information flow from the factory to the ECOFACT platform – to the LCA module (green box) – and back to the ECOFACT platform.

4.1 Description of the hypothetical factory

The hypothetical factory that is used as example throughout this chapter includes the production of two components and an assembly step to complete the final product. Component 1 contains aluminium and plastic, and component 2 contains steel. Figure 4 shows the factory flowchart. It shows the factory processes in green, as well as upstream processes and downstream waste management processes in blue. Next to the lines connecting the processes, it is indicated which parameters are used in the calculations. Table 2 shows the parameter names description.

The following characteristics of the factory process can be observed in Figure 4:

- The assembly process requires inputs of component 1, component 2 and electricity.
- The manufacturing of component 1 requires inputs of aluminium, high-density polyethylene (HDPE), electricity and heat (thermal energy) and produces waste/scrap of aluminium and HDPE.
- The manufacturing of component 2 requires inputs of steel and electricity.
- The production of aluminium scrap is assumed to all be sent to recycling, while the production waste of HDPE is assumed to be recycled, incinerated and/or landfilled.
- The electricity used by all processes is a combination of grid electricity mix and solar electricity.

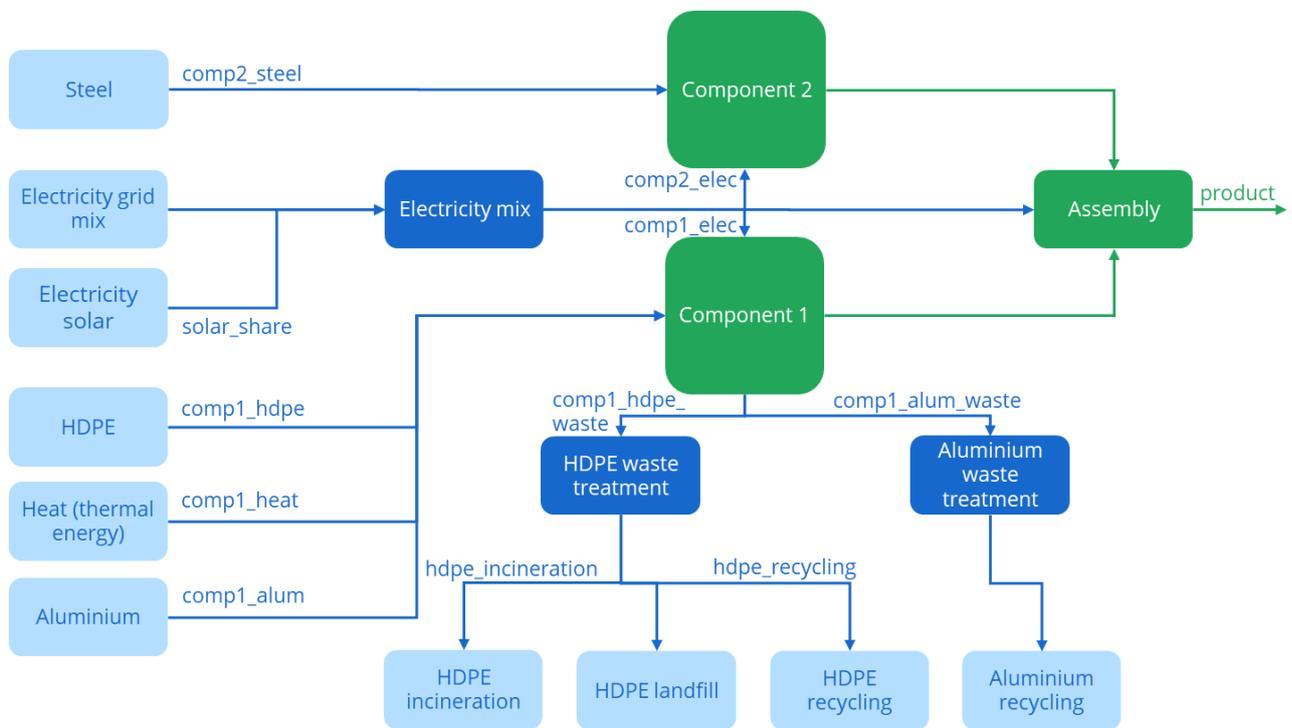


Figure 4: Hypothetical factory parametrized flowchart

Table 2: LCA model parameters description

Parameter name	Description	Unit
comp1_hdpe	HDPE amount required for component 1 manufacturing	kg
comp1_alum	Aluminium amount required for component 1 manufacturing	kg
comp1_elec	Electricity amount for component 1 manufacturing	kWh
comp1_heat	Heat amount for component 1 manufacturing	MJ
comp1_hdpe_waste	HDPE waste generated during component 1 manufacturing	kg
comp1_alum_waste	Aluminium waste generated during component 1 manufacturing	kg
comp2_steel	Steel amount required for component 2 manufacturing	kg
comp2_elec	Electricity amount for component 2 manufacturing	kWh
hdpe_incineration	Percentage of HDPE waste incinerated	%
hdpe_recycling	Percentage of HDPE waste recycled	%
solar_share	Percentage of solar energy in the electricity mix	%

4.2 Demonstration of the steps in the ECOFACT approach to dynamic LCA and LCC

4.2.1 Step 1: Define the goal and scope of LCA and LCC models

In this example, the goals of the LCA model of the hypothetical factory are:

- Continuous monitoring of the factory's carbon footprint per functional unit

- Evaluation of the carbon footprint over time for improved decision making and production planning

The functional unit of the hypothetical product system is 1 final product produced by the factory. The system boundary is from cradle-to-gate, that is, it includes the raw materials extraction and processing as well as all the related processes up until the factory gate. It also includes the waste management of waste generated from the factory processes. It does not include the downstream transportation, use or end of life of the product itself.

The internationally recognized environmental database Ecoinvent (version 3.8) [7] is used for the background system data. The background database contains the environmental emissions of materials, energy, transport and other economic activities.

The environmental KPIs to be calculated include a selection of impact categories. For this demonstration, the climate change impact category of the EF 3.0 impact assessment method [8] is used to assess the carbon footprint of the factory. In the ECOFACT demonstration factories, a larger set of indicators will be evaluated. More information about this can be found in Deliverable 4.1.

Finally, the SimaPro online platform, specifically the SimaPro Flow module [5], is used to model the hypothetical factory and the SimaPro API functionalities are used to perform the dynamic analysis.

4.2.2 Step 2: Identify data requirements

In our hypothetical factory, meters and sensors are installed to monitor the operation of processes and parameters of interest. The installed sensors and meters gather data related to energy consumption, raw materials, waste generation, waste treatment incineration and recycling shares, as well as the solar share in the electricity mix. These data are transferred to and stored by the data broker and are automatically updated every 15 min or on demand with new data measured in the factory.

4.2.2.1 Static data points

For our hypothetical factory, it is decided to keep the following data points as static:

- Process layout
- The product's bill of materials

This means that the model is built based on static data about these data points. If something changes in the layout or the bill of materials, the model would have to be updated manually.

4.2.2.2 Dynamic data points

There is a number of data points that will be dynamically updated at a specific frequency with updated values gathered from the sensors and meters deployed in the factory. These dynamic data points are listed in Table 3.

Table 3: Dynamic data points and update frequency

Type of data	Specific data	Unit	Update frequency
Electricity	Electricity consumption of component 1	kWh	Every 15 min



consumption	manufacturing		
Electricity consumption	Electricity consumption of component 2 manufacturing	kWh	Every 15 min
Thermal energy consumption	Thermal energy consumption of component 1 manufacturing	MJ	Every 15 min
Waste generation	Amount of aluminium waste generated during component 1 manufacturing	kg	Every 15 min
Waste generation	Amount of HDPE waste generated during component 1 manufacturing	kg	Every 15 min
Renewable energy share	Share of solar energy consumption during manufacturing	%	Every 15 min
Waste treatment	HDPE waste recycling share	%	Monthly
Waste treatment	HDPE waste incineration share	%	Monthly

4.2.3 Step 3: Map the required data to data sources

In our hypothetical factory, there are sensors and meters installed in the factory for all of the dynamic data points listed in Table 3. The sensors and meters send the data to the Local Data Acquisition System (e.g., a SCADA or BMS system). This is thus the data source for all the data points. The mapping of the required data to the data sources is shown in Table 4.

Table 4: Data sources for dynamic data points

Type of data	Specific data	Unit	Data source
Electricity consumption	Electricity consumption of component 1 manufacturing	kWh	Local Data Acquisition System
Electricity consumption	Electricity consumption of component 2 manufacturing	kWh	Local Data Acquisition System
Thermal energy consumption	Thermal energy consumption of component 1 manufacturing	MJ	Local Data Acquisition System
Waste generation	Amount of aluminium waste generated during component 1 manufacturing	kg	Local Data Acquisition System
Waste generation	Amount of HDPE waste generated during component 1 manufacturing	kg	Local Data Acquisition System
Renewable energy share	Share of solar energy consumption during manufacturing	%	Local Data Acquisition System
Waste treatment	HDPE waste recycling share	%	Local Data Acquisition System
Waste treatment	HDPE waste incineration share	%	Local Data Acquisition System



4.2.4 Step 4: Create parametrized LCA/LCC models of the factory processes

The next step, after defining the parameters that will be updated dynamically, is the creation of a parametrised LCA/LCC model in an LCA software that provides an API functionality. As discussed, the SimaPro online platform is used in this case study.

Parameters are the core of the dynamic LCA/LCC analysis. In particular, parameters can represent flows or other entities in an LCA model and can be adapted with updated values.

The parametrised model for the hypothetical factory is shown in Figure 4. It represents the production of one final product coming out of the assembly process at a moment in time. The model is fully parametrised. That means that values are represented by parameters. For instance, the production process for component 1 requires 10 MJ of thermal energy (for this particular moment in time). The thermal energy amount is represented by a parameter called “comp1_heat” (Figure 4). The value of this parameter will be dynamically updated every 15 minutes with updated values from the factory.

As stated in the goal and scope, the EF 3.0 impact assessment method is selected and is stored as a default method in the SimaPro online platform for this model. Finally, impact categories from different methods and additional indicators can all be combined in one custom method; several methods can be created too.

4.2.5 Step 5: Calculate baseline results

The baseline result can be obtained based on historical data. For the hypothetical factory this is calculated as 18.5 kg CO₂ eq. per produced unit for the previous year. It gives an initial insight into the climate change impact hotspots. At this point, a detailed analysis can take place to identify important carbon footprint contributors that could lead to model modifications or alternative data requirements. The baseline carbon footprint result can set the benchmark for environmental improvements that need to be achieved in the factory in order to reduce that value.

4.2.6 Step 7: Set up live link to feed data to the LCA/LCC models

4.2.6.1 Setting up the API and requesting updated LCA/LCC results

When the parametrised LCA model is in place, the API can be used to request updated LCA/LCC results. For the calculation of the life cycle environmental impact of the hypothetical factory, the ECOFACT platform will connect to the SimaPro online platform by triggering the relevant SimaPro API requests to get updated LCA/LCC results. This request will contain a JSON file with a list of the LCA model parameters and their updated values gathered from the sensors and meters in the factories. After the calculation is completed, another request will be called to retrieve the results of the calculation from the SimaPro platform. This request will return a JSON file that includes the LCA/LCC results. Specifically, the workflow is the following:

1. **Login/Authentication**: POST request to receive an API access token.
2. **Calculation**: POST request to start an LCA/LCC calculation with updated values from the factory.
3. **Calculation Status (Optional)**: GET request to retrieve the state of the calculation (the LCA/LCC calculation takes a few seconds to be executed. Status types: Not Found, Calculating, Calculated, Calculation Failed, Storing, Store Failed, Stored).



4. **Calculation Results:** POST request to retrieve the results of the LCA/LCC calculation from step 2.

Step 1 will return an access token that needs to be used from the rest of the requests. Step 2 will trigger an LCA/LCC calculation and will return a calculation ID. Step 3 uses the calculation ID to return the status of the calculation. Finally, step 4 uses the calculation id to return a JSON file with the LCA/LCC results. The basic structure of the requests is shown below.

The python programming language is used to demonstrate the SimaPro API requests.

1. Login/Authentication

The first request provides access to the SimaPro online platform and returns an access token. The access token is stored and used in the subsequent requests.

Example request

```
import requests
import json

url = "https://api.simapro.com/token"

payload = json.dumps({
    "email": "email(string)",
    "password": "password(string)"
})

headers = {
    'Content-Type': 'application/json'
}

response = requests.request("POST", url, headers=headers, data=payload)

print(response.text)
```

Example response

```
{
  "Status": 200,
  "Result": {
    "AccessToken": {
      "Token": "AccessToken(string)",
      "ExpiresIn": 3600,
      "CompanyId": "3fa85f64-5717-4562-b3fc-2c963f66afa6"
    },
    "RefreshToken": " RefreshToken(string)"
  },
  "Errors": null
}
```

2. Calculation

The calculation request is the main request that triggers an LCA/LCC calculation in the SimaPro platform. The URL of the calculation request requires the project ID (string type) which is the ID of the project that contains the parametrised LCA model of the



hypothetical factory. The request header requires the access token returned in step 1, as well as the content type. The request payload contains the list of the LCA parameters and their values. These values will be dynamically updated with the data gathered from the hypothetical factory. Thus, each time a calculation request is triggered, the payload (which is the body of the request that contains the data that are sent to the online platform) will include the latest values measured in the factory. For instance, in the following example the 'comp1_elec' parameter, which represents the electricity consumption of the manufacturing of component 1, has the value of 5 (kWh). If the electricity consumption reduces to 4 kWh throughout the day, for example, due to some changes in the production parameters of the factory machines, then in the new calculation request the 'comp1_elec' parameter will receive the value of 4 (kWh).

It should be noted here that in the actual ECOFACT implementation the payload of the request will include the relevant values measured from the consumption monitoring systems of the factory sites per time interval, as well as the total number of units produced per time interval. The LCA/LCC module will divide the two data points in order to get the values per functional unit. For simplicity reasons in this demonstration, the parameter values have been pre-calculated per functional unit and have been used in the request's payload.

As discussed earlier, the EF3.0 impact assessment method is selected and stored as a default method in the SimaPro online platform for this model. For that reason, the payload of the calculation request only contains a list of parameters. However, it is also possible to trigger a calculation request using a different impact assessment method. The selection of a different LCIA method or other calculation features will have to be included within the payload of the request. This is demonstrated later in chapter 4.2.6.2.

Finally, the response of the calculation request contains the calculation ID (string type) and the status of the calculation. The LCA calculation requires a few seconds to be executed. During the calculation execution the status is "calculating".

Example request

```
import requests
import json

url = "https://api.simapro.com/calculation/projectId"

payload = json.dumps([
    {
        "name": "solar_share",
        "value": "0"
    },
    {
        "name": "hdpe_incineration",
        "value": "0.4"
    },
    {
        "name": "hdpe_recycling",
        "value": "0.3"
    },
    {
        "name": "comp1_hdpe_waste",
        "value": "1"
    },
])
```



```

    {
      "name": "comp1_alum_waste",
      "value": "0.05"
    },
    {
      "name": "comp1_hdpe",
      "value": "2"
    },
    {
      "name": "comp1_heat",
      "value": "10"
    },
    {
      "name": "comp1_alum",
      "value": "0.2"
    },
    {
      "name": "comp1_elec",
      "value": "5"
    },
    {
      "name": "comp2_elec",
      "value": "3"
    },
    {
      "name": "comp2_steel",
      "value": "0.5"
    }
  ]
}
headers = {
  'Authorization': 'Bearer+' +' '+ 'AccessToken (string) ',
  'Content-Type': 'application/json'
}
response = requests.request("POST", url, headers=headers, data=payload)
print(response.text)

```

Example response

```

{
  "Status": 200,
  "Result": {
    "CalculationId": "fdc5b799-020d-4e4d-b35d-b9394416662a",
    "Status": "Calculating",
    "CalculationMetaData": null
  },
  "Errors": null
}

```

3. Calculation status request (optional)

Before retrieving the results of the calculation, one might want to check the status of the calculation. Checking the status of the calculation is done through a GET request. The request URL requires the calculation ID that was returned in the calculation request in the previous step. The request header requires the access token returned in step 1. If

the calculation is successfully completed, the response of the calculation status will return "stored", which means that the LCA/LCC calculation has been completed and the environmental impact assessment results have been stored.

Example request

```
import requests

url = "https://api.simapro.com/calculation/state/fdc5b799-020d-4e4d-b35d-b9394416662a"

payload={}
headers = {
    'Authorization': 'Bearer'+ ' '+AccessToken(string) '
}

response = requests.request("GET", url, headers=headers, data=payload)

print(response.text)
```

Example response

```
{
  "Status": 200,
  "Result": "Stored",
  "Errors": null
}
```

4. Calculation results

The final request is to retrieve the results of the LCA/LCC calculation. This is done through a post request that requires in the URL the calculation ID that was returned in step 2. The request header requires the access token returned in step 1, as well as the content type. The response will contain the environmental impact assessment results, the method and impact category names and other relevant meta data. The response can contain all the relevant information of an LCA, such as the total characterized LCA impact, the results per tier, the process contribution per impact category, the inventory data, normalized and weighted results. Relevant data are returned in the format of tables so that is straightforward to visualize.

In this example, we limit the response by requesting the total LCA impact only. This is indicated in the request payload as "DTotal" which is the name of the table that contains that total LCA characterized results within the JSON file. The response contains the life cycle assessment results of a selected impact category of the EF 3.0 method, namely the "climate change" impact category.

Example request

```
import requests
import json

url = "https://api.simapro.com/calculation/result/fdc5b799-020d-4e4d-b35d-b9394416662a"
```



```

payload = json.dumps({
    "value": "DTotal"
})
headers = {
    'Authorization': 'Bearer'+ ' '+AccessToken(string) ',
    'Content-Type': 'application/json'
}

response = requests.request("POST", url, headers=headers, data=payload)

print(response.text)

```

Example response

```

{
  "Status": 200,
  "Result": {
    "AnswerSetId": null,
    "Results": [
      {
        "Name": "Tabular Results",
        "Tables": [
          {
            "Table": "DTotal",
            "Columns": [
              "Impact Category",
              "Unit",
              "Total"
            ],
            "ColumnTypes": [
              "string",
              "string",
              "number"
            ],
            "Rows": [
              [
                "Climate change",
                "kg CO2 eq",
                "18.976598017784937"
              ]
            ]
          }
        ]
      },
      {
        "Name": "Chart Results",
        "Tables": []
      }
    ],
    "CalculationMetaData": {
      "MethodName": "ECOFACT_Selected ICs from EF 3.0 Method",
      "NoSubstances": false,
      "HideDamageAssessment": true,
      "HideWeighting": true,
      "HideNormalisation": true,
      "HasAccessToShare": true,
      "ShowShareButton": true,
      "Warnings": ["string"],
      "IncludedResults": ["string"],
      "ImpactCategoryNames": [

```

```

        {
            "Id": "c4353346-7011-423e-b0a2-730df5a81179",
            "UniqueName": "Climate change (ECOFACT_Selected ICs
from EF 3.0 Method)"
        }
    ],
    },
    "Errors": null
}

```

4.2.6.2 Additional remarks on the calculation request

In this demonstration, the life cycle impact assessment EF 3.0 method and the climate change impact category of that method have already been pre-selected and stored in the SimaPro online platform as a default calculation setting for the hypothetical factory model. However, one might want to be able to request LCA/LCC results using different available methods. For instance, one might want to use the IPCC method to calculate the carbon footprint, the EF 3.0 method to calculate the “resource use, minerals and metals” impact category or a special method to calculate LCC. The method, as well as other options, can be defined in the calculation request (in step 2). Thus, the calculation request could contain a list of parameters with updated values, as well as a method selection and other relevant options.

In the following example, a calculation request is setup to include a different impact assessment method than the pre-selected EF 3.0 method. This is done in the payload of the request. In particular, the ReCiPe 2016 midpoint hierarchical method is selected. Furthermore, this calculation request requires an LCA “contribution analysis” and sets the number of “tiers” to be analysed. Thus, in the payload of the calculation request, any relevant life cycle impact assessment requirements can be set.

Example request

```

import requests
import json

url = "https://api.simapro.com/calculation/projectId"

payload = json.dumps({
    "Id": "00000000-0000-0000-0000-000000000000",
    "MethodId": "210215cc-99e5-4621-a7e0-f5a09ab530fa",
    "MethodName": "ReCiPe 2016 Midpoint (H)",
    "NormalisationSetId": "86b7bb89-8904-4faf-8e56-2d8bccf13b2b",
    "WeightingSetId": "c5399d7e-67e1-4c18-a0f2-a745f2fdde32",
    "CalculationItems": [
        {
            "ParameterModificationValues": [
                {
                    "name": "solar_share",
                    "value": "0"
                },
                {
                    "name": "hdpe_incineration",
                    "value": "0.4"
                },
                {

```

```

        "name": "hdpe_recycling",
        "value": "0.3"
    },
    {
        "name": "comp1_hdpe_waste",
        "value": "1"
    },
    {
        "name": "comp1_alum_waste",
        "value": "0.05"
    }
    # other parameters...
]
}
],
"ContributionOptions": {
    "ShowContributions": True,
    "Tiers": 3
}
})
headers = {
    'Authorization': 'Bearer'+ ' '+AccessToken(string)',
    'Content-Type': 'application/json'
}

response = requests.request("POST", url, headers=headers, data=payload)

print(response.text)

```

4.2.6.3 Demonstrating updated values per time interval: new API calculation requests

When the parametrized LCA model and the API functionality are in place, the tool is ready for use. Table 5 contains hypothetical updated parameter values for nine subsequent LCA calculations. That is, the parameters are assumed to be updated with new data measured in the factories every 15 minutes. It should be noted that the HDPE incineration and recycling rates are updated in a monthly frequency. In this case they have been updated in t8 time interval, assuming that this is their monthly update. The rows in Table 5 represent the LCA parameters and the columns represent values for the different moments in time. For instance, t0 represents the values measured for the manufacturing of one final product at 9.00 o'clock, t1 represents the values measured at 9.15, t2 represents the values measured at 9.30 and so on. Parameter values that changed per time interval compared to the values recorded in t0 are indicated in red colour.

Table 5: Model parameters and their updated values per time interval

Parameter\Time intervals	t0	t1	t2	t3	t4	t5	t6	t7	t8
solar_share (0-1)	0	0	0	0.2	0	0	0.3	0.7	0.7
hdpe_incineration (0-1)	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.3
hdpe_recycling (0-1)	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.3	0.4

comp1_hdpe_waste (kg)	1	1	1	1	0.5	0.5	0.5	0.3	0.3
comp1_alum_waste (kg)	0.05	0.05	0.05	0.05	0.05	0.01	0.01	0.01	0.01
comp1_hdpe (kg)	2	2	2	2	2	2	2	2	2
comp1_heat (MJ)	10	8	8	8	12	12	12	15	15
comp1_alum (kg)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.2
comp1_elec (kWh)	5	5	4	4	5	10	10	10	10
comp2_elec (kWh)	3	3	2	2	3	3	3	3	3
comp2_steel (kg)	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5

Every 15 minutes, a new API calculation request will be sent to the Simapro platform that includes a new list with updated parameter values. For instance, the calculation request for t5 will have the following format.

Example request for t5 time interval

```
import requests
import json

url = "https://api.simapro.com/calculation/projectId"

payload = json.dumps([
    {
        "name": "solar_share",
        "value": "0"
    },
    {
        "name": "hdpe_incineration",
        "value": "0.4"
    },
    {
        "name": "hdpe_recycling",
        "value": "0.3"
    },
    {
        "name": "comp1_hdpe_waste",
        "value": "0.5"
    },
    {
        "name": "comp1_alum_waste",
        "value": "0.01"
    },
    {
        "name": "comp1_hdpe",
        "value": "2"
    },
    {
        "name": "comp1_heat",
        "value": "12"
    },
    {
        "name": "comp1_alum",
        "value": "0.2"
    },
    {
```



```

    "name": "comp1_elec",
    "value": "10"
  },
  {
    "name": "comp2_elec",
    "value": "3"
  },
  {
    "name": "comp2_steel",
    "value": "0.5"
  }
])
headers = {
  'Authorization': 'Bearer'+ ' '+ 'AccessToken (string) ',
  'Content-Type': 'application/json'
}

response = requests.request("POST", url, headers=headers, data=payload)

print(response.text)

```

When the calculation is completed, a request to retrieve the calculations results will be sent, and the results will be returned as a JSON file that can be visualized and further processed.

4.2.7 Step 8: Configure data management and storing

To be able to keep track of historic records, the list of parameters and their values per moment in time need to be stored. This can be done by storing the parameter set for each calculation request. The parameter set will have a unique ID.

In the case of the hypothetical factory, nine calculation requests that contain a unique parameter set each, will be sent (one for every column in Table 5). The nine parameter sets can be stored, each having a unique ID. When one wants to retrieve historic records, a calculation request can be send using the parameter set ID from that past moment.

4.2.8 Step 9: Configure dashboards

Different dashboards for the LCA/LCC visualizations can be set up for different users. Dashboards can be customized to the detail and time resolution that is needed by a user. For this the example of the hypothetical factory, the total carbon footprint per time interval is visualized, as seen in Figure 5.

4.2.9 Step 11: Continuously monitor and improve

Figure 5 shows the total carbon footprint per product manufactured in the hypothetical factory per time interval, as recorded in Table 5. Since results are updated every 15 minutes, the nine time intervals (t0-t8) represent the carbon footprint per product within a 2 hour time frame. The first column of Figure 5 represents the carbon footprint baseline result as calculated for the previous year (discussed in step 5).



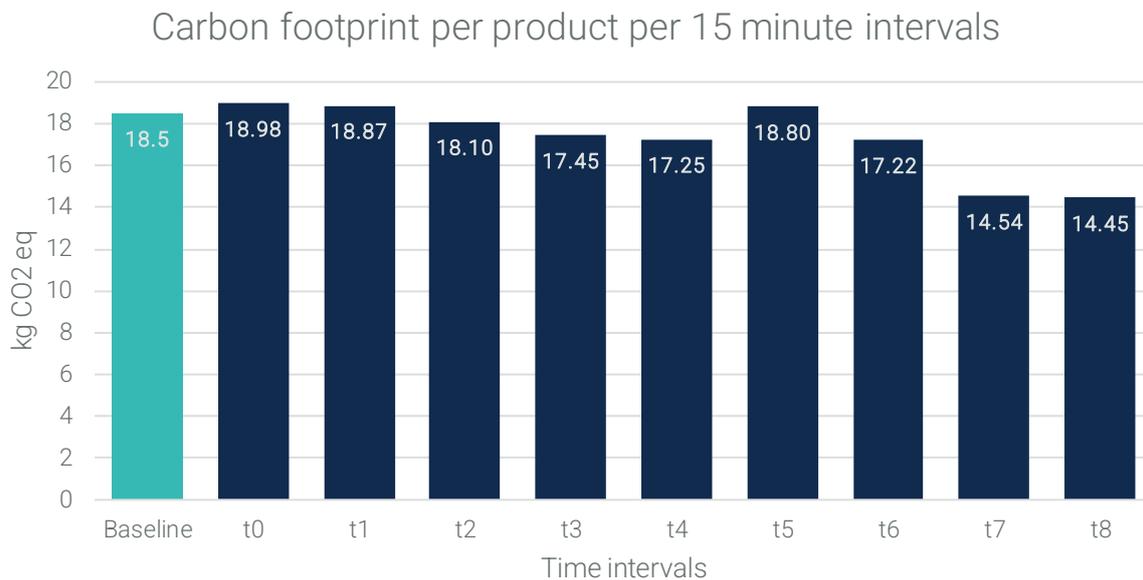


Figure 5: Carbon footprint per time interval

From t0 to t3, there is a slight reduction in the carbon footprint. The reason is that there were reductions in the electricity required for the production of component 1 and component 2, as well as in the thermal energy required for the production of component 1, see Table 5. These energy improvements could have been the result of, for instance, changes in some production parameters in the hypothetical factory.

T4, represents a hypothetical but plausible trade-off. The thermal energy for the production of component 1 increased which resulted in 50% reduction in HDPE waste, as recorded in Table 5. That caused a further reduction of the carbon footprint. By monitoring the parameter changes in the factory in real time such potential trade-offs would become evident.

T5 also represents a similar like t4 hypothetical but plausible trade-off. For this instance, there is a significant increase in the carbon footprint compared to the previous time intervals. The reason is that the electricity required for component 1 production was doubled which resulted in less aluminium waste. The benefits from the aluminium waste reduction were not sufficient to compensate for the increased electricity and that resulted in increased carbon footprint. Again, these values are hypothetical, but with the real-time monitoring such parameter correlations would become observable revealing new insights and patterns over time.

In t6 however, while keeping the electricity and aluminium waste parameters same as t5, the carbon footprint has been significantly reduced. The reason is, that in t6, the electricity mix changed to include more solar power, improving its emissions profile. Thus, a 30% solar-based electricity reverses the increase in carbon footprint that took place in t5.

Moreover, in t7, there is a further decrease in the carbon footprint mainly due to the 70% solar electricity in the mix.

Finally, there is an additional reduction in the carbon footprint in t8, due to an increase in the rate of recycling for HDPE waste and a subsequent decrease in the HDPE incineration.

Although the parameter values are hypothetical, this demonstration shows the range of changes that can be tracked when the factory is continuously monitored and when the results are updated in real-time.

To summarise the results, within a two hour time frame there were significant changes in the carbon footprint of the product. Specifically, in t0, the carbon footprint of the product was 18.98 kg CO₂ eq., while in t8, the carbon footprint of the product was 14.45 kg CO₂ eq. Thus, we can observe the fluctuation of the impact within this two hour time frame for this hypothetical demonstration.

4.2.9.1 Interpreting the results – Unlocking new insights with dynamic analysis

The changes in the parameters that occurred in the hypothetical factory for the different time intervals could be the result of:

- Changes in the production parameters in the factory.
- Machines that were underperforming.
- Ongoing maintenance.
- Efficiency improvements.
- Reduction of downtime.
- Energy mix changes.
- Other actions that took place in the factory.

The energy mix can change throughout the day or during a season. For instance, a factory might have its own photovoltaic panels installed which change the energy mix when the sun is shining during the day. Thus, real-time LCA can reveal:

- Seasonal variations in environmental performance. For instance, when a factory performs better during the summer months due to lower heating needs or the use of a more renewable electricity mix.
- Daily or hourly variations in the life cycle impacts of a factory due to changes in the settings and operational parameters of production machineries.
- Downtime in assembly lines or production processes that affects the environmental performance of a factory.
- The correlation of environmental impacts with production parameters and the identification of new insights and patterns over time.

4.2.9.2 Targeted actions based on insights from dynamic LCA

For hypothetical factory example, new insights from the analysis can unlock improvement opportunities that would not have been foreseen with the traditional, static LCA approach. This can lead to targeted action, directly applied to improve the factory's environmental performance.

Such targeted actions could include:

- Planning the operation of energy intensive processes at maximum capacity when weather conditions are favourable for using renewable electricity.



- Adjusting the production parameters, based on the hypothetical trade-off presented for t5, t6 and t7, can lead to improved environmental performance. In t5 it was assumed that the increase in the electricity consumption led to waste generation reduction. However, during t5, the electricity mix was not favourable for such an increase in the electricity consumption which led to increased carbon footprint. On the other hand, when the solar electricity share increased, the carbon footprint of the factory significantly reduced (in t6 and t7). Thus, during the times of increased renewable electricity, the factory operator can prioritize increasing the manufacturing electricity consumption that would lead to reduced waste generation, resulting in reduced carbon footprint. While in the case that the energy mix is not favourable, the factory operator can choose to reduce the manufacturing electricity consumption, even though this action could cause an increase in waste generation. Real-time monitoring and impact assessment can help identify such correlations of production parameters and environmental impact. That enables the identification of new insights and patterns over time leading to targeted actions for further environmental improvements.
- It might be that the performance of a machine and its waste generation is related to machine maintenance. Therefore, it is possible that higher impact results indicate that maintenance is needed, which can be an input for maintenance planning. Maintenance can also be scheduled for a day/time of day when high environmental impact results are expected, based on patterns observed in the past, thereby pausing production during a peak in impact.

Each specific action applied in the factory can also be evaluated in real-time, thus creating a positive feedback loop to enable further improvements.



5 Discussion

5.1 Dynamic LCA vs traditional LCA

Being able to observe the changes in the environmental performance of a product over time is novel information. In traditional – static – LCA, life cycle impact is typically assessed as an average impact of a product over a period of a year, using average yearly material and energy consumption and production values. In this dynamic, real-time approach, the impact of a product is assessed continuously. Thus, the impact of changes in the factory operation is recorded instantly and in an automated way.

This real-time assessment of environmental impacts opens up new opportunities. The traditional LCA approach is useful for identifying burdens, opportunities and trade-offs in product development and it allows for product comparisons. The real-time approach goes beyond traditional LCA by unlocking new temporal insights that enable targeted improvement actions in the factories.

5.2 On demand calculation requests and additional logic

The environmental impact calculation requests do not have to be triggered only on the pre-specified time intervals. The user of the tool (i.e., factory operator) can also have the option to calculate the environmental impact on demand, for instance to immediately test a change that was applied in the factory. Furthermore, logic can also be applied in the tool to automatically trigger a new environmental impact calculation request when it detects a “significant” alteration in specific parameters. This information can be used by the decision support system to provide suggestions to the user about improvement actions.

5.3 Life cycle costing

In this demonstration, the focus was on the life cycle assessment of the hypothetical factory. The same procedure can be applied to assess the life cycle costing of the manufacturing of a product. In particular:

- Additional parameters can be set to store materials costs, energy costs and waste management costs.
- Life cycle cost calculation can be handled similarly to the life cycle impact assessment calculation, using the same API as demonstrated earlier. That is, when the LCC needs to be assessed, a calculation request will be sent including a list of parameters and their values as a payload, as well as the specific LCC method to be used (similar to what was described in section 4.2.6.2).

5.4 Future potential of real-time LCA: predictive analytics

The continuous environmental impact assessment monitoring could potentially lead to new interesting (research) questions that are outside the scope of the ECOFACT project.

For example, the data gathered from the factories and their associated LCA/LCC results could be used to train models (algorithms). Specifically, models can be trained using the large number of inputs (parameter values) and outputs (LCA/LCC results) that will be



generated over time. These models can be potentially further trained with additional data that come from sources beyond the scope of – traditional – LCA, such as weather data, carbon emission prices.

Applying analytics can allow the identification of patterns, parameter correlation with impacts or other insights. Machine learning can be used to predict impacts of specific actions, further optimize product manufacturing, reduce costs and environmental risks of new products and open up new developments.



6 Conclusions

This deliverable laid out the ECOFACT approach to performing a dynamic (real-time) LCA and LCC in a factory environment. It shows the role of the API for the online LCA/LCC module in enabling environmental footprint calculations in real-time and at scale.

The deliverable briefly describes the ECOFACT platform, and then lays out a 11-step approach for performing a dynamic LCA and LCC study for a manufacturing company.

The ECOFACT technical solution consists of three main layers: the edge layer, the data broker layer and the apps and services layer. The edge layer is the layer installed at the manufacturing site and is not part of the ECOFACT platform itself. The technical solution was discussed in chapter 3.

The steps for carrying out a dynamic LCA/LCC study for a manufacturing company (chapter 3) are summarized below:

- Step 1: Define the goal and scope of LCA and LCC models
- Step 2: Identify data requirements
- Step 3: Map the required data to data sources
- Step 4: Create parameterized LCA and LCC model of factory processes
- Step 5: Calculate baseline results
- Step 6: Define and evaluate scenarios, perform sensitivity analysis and refine models
- Step 7: Set up live link to feed data to the LCA/LCC models
- Step 8: Configure data management and storing
- Step 9: Configure dashboards
- Step 10: Configuring decision support functionality
- Step 11: Continuously monitor and improve

The main steps on performing a dynamic, real-time, automated LCA/LCC, using the SimaPro API solution, were demonstrated with an example in chapter 4.

Performing dynamic, real-time, automated LCA/LCC using an API provided by the LCA/LCC module can lead to new insights that can enable targeted actions in a factory to reduce its environmental footprint; and it can open up new research questions and developments.



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